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Effect of $CdCl_2$ treatment on structural and electronic property of CdTe thin films deposited by magnetron sputtering

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ABSTRACT

The structural and electrical properties of the magnetron sputtered CdTe thin films with subsequent $CdCl_2$ solution treatment have been studied with a major focus on the influence of $CdCl_2$ treatment to achieve high quality thin films. In this study, CdTe films with a thickness of 1.5 to 2 μm have been grown using the magnetron sputtering technique on top of glass substrate at an optimized substrate temperature of 250 °C. Aqueous $CdCl_2$ concentration varied from 0.3 mol to 1.2 mol with the annealing temperature from 360 °C to 450 °C. The surface roughness of the films increases with the increase of solution concentration, while it fluctuates with the increase of annealing temperature. The density of nucleation centers and the strain increases for the films treated at 360 °C with 0.3 M to1.2 M while the grain growth of the films reduces. However, these strains are released at higher annealing temperatures, resulting in reduced dislocation densities, structural defects as well as increased crystalline property and grain size. The carrier concentration increases with the increase of treated $CdCl_2$ concentration and subsequent annealing temperature. The highest carrier concentration of $1.05 \times 10^{14}/cm^3$ was found for the CdTe thin films treated with 0.3 M $CdCl_2$ solution followed by an annealing treatment at 420 °C for 20 min.

1. Introduction

CdTe is one of the most promising semiconductor materials in thin film heterojunction solar cells attributing to its ideal energy band gap (Eg) of 1.45 eV for solar cells. Moreover, it has the highest average atomic number among the II-VI semiconductor compounds, the highest iconicity, the largest lattice parameter, the least negative formation enthalpy, and the lowest melting temperature [1]. All the above features with higher absorption coefficients (5.1×10^5/cm) make it an ideal and attractive material for heterojunction thin film solar cells. Small-area CdTe heterojunction solar cells have already achieved efficiency of 16.5% in the laboratory and 11% in commercial modules [2–5]. However, knowledge of basic properties of the materials and processes involved in device fabrication is limited, including the $CdCl_2$ heat treatment. Although this heat treatment has been studied by many researchers in the past years [6–12], the exact effects of this treatment are not yet completely conclusive. Recrystallization and grain growth are observed after this treatment in some cases [13], but not in others [14]. It has also been reported that the recrystallization of the CdTe films due to this treatment is dependent on the initial stress state of the material, and the type and conditions of the treatment [15]. However, even this treatment does not recrystallize the films in some cases; the importance of this stage is well acknowledged, because it decreases the density of deep levels inside the bandgap and changes the defect structure, resulting in a better device performance [16]. The effect of $CdCl_2$ treatment has also not been studied yet for ultra-thin (1.5–2.0 μm) CdTe thin films deposited from the sputtering technique with low deposition rate or well-known close-spaced sublimation with a higher deposition rate.

Cadmium chloride treatment can be carried out either as an in-situ treatment or as a post-deposition treatment. However, post-deposition treatment is the most accepted method due to its inherent process flexibility [17,18]. Conventionally, post deposition $CdCl_2$ treatment has been carried out as a solution treatment because it is simple and easy. In this solution treatment, specific amount of $CdCl_2$ is first dissolved in methanol and then applied on deposited CdTe thin films by dipping or spraying or spin coating techniques. Afterwards, CdTe films are heated in air or vacuum at 400 to 420 °C for 10 to 30 min, during which the electrical and structural properties of CdTe films get suitably modified [18]. The heat treatment is generally followed by a hot water wash to remove the excess $CdCl_2$. This technique is quite simple to perform and low cost.

This work extends the range of knowledge for the structural and electrical properties of ultra-thin CdTe thin films, which are less than 2 μm thick as defined here and other literatures. The CdTe films are deposited by magnetron sputtering with post-growth $CdCl_2$ treatment

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through solution and a subsequent annealing in 2.66 kPa N_2/O_2 ambient. The solution used in this process was diluted not in methanol but in deionized (DI) water. This study has been conducted for the first time to look into such effects in 1.5 μm thick sputtered CdTe thin films. The changes on the structural and electrical properties of CdTe thin films were observed from X-ray diffraction technique (XRD), atomic force microscopy (AFM), variable pressure scanning electron microscopy (VPSEM) and Hall Effect measurement techniques.

2. Experimental details

Magnetron sputtering is a well-established physical vapor deposition technique to make samples with precise surface morphology with advantageous optical and electronic properties. It is at ease with deposit metallic and compound thin films for a wide range of applications [19]. Commercially available soda lime glasses were prepared to deposit CdTe by cleaning in ultra-sonic bath, degreased by ethanol-acetone-ethanol and deionized water for 5 min, respectively. Degreased glasses were dried by dry N_2. The CdTe thin films of 1.5–2.0 μm thick are then prepared by sputtering technique at a 250 °C substrate temperature on top of a glass. The working pressure of argon ambient was 1.87 Pa during the deposition and the rate of deposition was 0.5 Å/s maintained at the RF power of 30 W. The samples were kept in the deposition chamber until the temperature cooled down to room temperature. Then, the solutions of 0.3, 0.6, 0.9 and 1.2 M are prepared in DI water and the samples are dipped into these solutions for 10 s. The samples are then dried in air about 10 min. and they are annealed in a vacuum furnace of N_2/O_2 (99:1) ambient for 20 min. at 2.66 kPa pressure at 390 °C–450 °C. The chamber pressure was maintained constant with continuous nitrogen gas flow of 40 ml/min supplied during annealing. At the end of the annealing process, the samples were left in the annealing chamber until the chamber temperature returned to room temperature. The resultant samples were then washed by warmed DI water several times to remove the $CdCl_2$ residues. The deposited films prepared for these studies are divided into two categories. For the first category, the solution concentration was changed to 0.6 M, 0.9 M and 1.2 M with a fixed treated temperature of 360 °C, whereas annealing temperature was changed to 390 °C, 420 °C and 450 °C with fixed solution concentration 0.3 M for the other category. One deposited film treated with 0.3 M solution and annealed at 360 °C temperature is a base or reference sample in both categories.

The physical and structural properties were investigated using XRD, AFM and VPSEM. The XRD patterns were recorded in the 2θ range 20° to 60° using Cu Kα radiation of wave length, $\lambda = 1.5408$ Å using BRUKER aXS-D8 Advance Cu-Kα diffractometer. The change of crystallite size, micro-strain, and dislocation density etc. were analyzed from the XRD patterns. Surface topography analysis of the samples was carried out in a semi-contact mode by Atomic Force Microscope (AFM) of 'INTERA PRIMA, NT-MDT' brand. The surface topography, roughness and grain size of the films were observed from the AFM images and SEM images. The grain growth is observed from SEM images carried out at operating voltage 3.0 kV by VPSEM 'LEO 1450 Vp'. The electrical properties such as carrier concentration, mobility, resistivity and Hall coefficients are measured by Hall Effect measurement tool 'ECOPIA 3000'. The film thickness was measured from SEM images as well as double weight methods in which the mass of the samples was measured before and after deposition to calculate the thickness. The thicknesses found in both cases were almost the same, ranging from 1.5 to 2.0 μm.

3. Results and discussions

3.1. XRD analysis

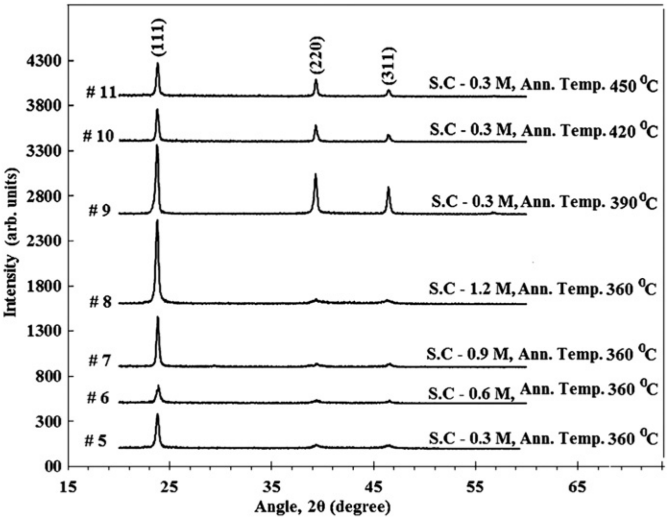

Fig. 1. XRD diffraction patterns of $CdCl_2$ treated CdTe samples (5, 6, 7 and 8) with different solution concentrations and annealed at 360 °C; samples (9, 10 and 11) annealed at different temperatures with treated solution concentration of 0.3 M.

X-ray diffraction patterns were investigated to find the impact of $CdCl_2$ solution treatment on the CdTe film crystalline property. Fig. 1 shows the XRD pattern of $CdCl_2$ solution treated CdTe film with different solution concentration and at different annealing temperatures. The treatment temperature was kept constant at 360 °C while the treatment condition, i.e. the solution concentration was varied from 0.3 M to 1.2 M for the samples 5, 6, 7 and 8. On the contrary, the treatment condition, i.e. solution concentration, was kept constant, while the annealing temperature was varied from 360 °C to 450 °C for the samples 5, 9, 10 and 11. The diffraction peaks observed for all the films deposited on glass were around $2\theta = 23.80$, 39.0 and 46.49° corresponding to (111), (220) and (311) planes of CdTe thin films, respectively, which are confirmed by JCPDS X-ray powder file data (15-0770). The lattice parameter 'a' for cubic phase structure [hkl] for both types of films has been determined from the Brag's law and Vegard's law [20,21]:

$$d_{hkl} = (\lambda/2)\operatorname{cosec}\theta \tag{1}$$

$$a_{cubic} = d_{hkl}\left(h^2 + k^2 + l^2\right)^{1/2} \tag{2}$$

where, λ is the X-ray wavelength (0.15406 nm), *d* is the spacing between the planes in the atomic lattice, *θ* is the angle between the incident ray and the scattering planes, and *a* is the lattice constant.

In order to obtain more structural information, the mean crystallite sizes (D) of the films are calculated using Scherrer formula [22]:

$$D_{hkl} = 0.9\lambda/(\beta\cos\theta) \tag{3}$$

where, λ is the X-ray wavelength (0.15406 nm), and β is the full width at half maximum [FWHM] of the film diffraction peak at 2θ, where θ is the Bragg diffraction angle.

It has been observed that the deposited CdTe film is polycrystalline in nature with random orientation, and therefore, large number of grains with various relative positions and orientations cause variations in the phase difference between the wave scattered by one grain and the others. The total intensity scattered by all grains is equal to the sum of individual intensities scattered by each grain. By varying displacement of the atoms with respect to their reference-lattice positions, the lattice strains are developed. Simply, these phenomena can be defined by micro-strain. The origin of micro-strain is related to lattice 'misfit', which in turn, depends upon the growing conditions of the films. The micro-strain (ε) developed in the thin films are calculated from the relation [23,24],

$$\text{Micro}-\text{strain}, \varepsilon = \beta/4\tan\theta \tag{4}$$

where, θ and β have their usual significances. It is well known that growth mechanism of thin films involving dislocation is a matter of importance. Dislocations are an imperfection in a crystal associated with misregistry of the lattice in one part of the crystal with respect to another part. Unlike vacancies and interstitial atoms, dislocations are not equilibrium imperfections. The dislocation density of thin films are calculated by the Williamson and Smallman's relation [25],

$$\delta = n/D^2 \tag{5}$$

where, *n* is a factor, which is almost equal to unity for minimum dislocation density and *D* is the grain size. It has been observed that for the corresponding planes, micro-strain values and dislocation densities are higher for untreated CdTe thin films [26]. All the results found from the above analysis are presented in Table 1 and Fig. 2 in which values of lattice constant, D, ε and δ are compared for treated CdTe thin films with respect to the solution concentration and treated temperature.

Fig. 1 shows the XRD diffraction patterns for deposited CdTe thin films. It is quite clear that all samples showed an intense peak at 2theta = 23.78°, which corresponds to the (111) cubic plane of CdTe thin films. This shows that the deposited CdTe films are sphalerite structured with (111) crystallographic plane orientation. To understand the effect of solution concentration and treated temperature more clearly, Fig. 2 has been drawn with respect to the treated parameters versus plane/orientation intensity. From Figs. 1 and 2, it has been observed that the (111) plane's intensity for the samples 5, 6, 7 and 8 increases by following the solution concentration, whereas (220) and (311) plane intensities do not or change very little. This indicates that the domination of (111) plane over other planes with the increase of solution concentration and the films become strongly (111) plane oriented by losing their polycrystalline form. This may have happened due to the lack of enough thermal stress during the treatment. On the other hand, for the samples 5, 9, 10 and 11, where the samples were annealed at 360 °C, 390 °C, 420 °C and 450 °C, the planes (220) and (311) became stronger with respect to the (111) plane. As seen in Fig. 2, the film's (111) plane orientation increases sharply to some extent at 390 °C, then gets down and has no change above 420 °C of annealing temperature. From this study, it has been observed that the annealing temperature of 360 °C is not sufficient enough for recrystallization and nucleation. However, annealing at 390 °C gives a standard thermal stress and 450 °C demonstrates over thermal stress to the films, which decreases the crystallinity. However, from this phenomenon, it has been observed that the effect of annealing temperature is more impactful than the solution concentration during the post growth annealing treatment of CdTe thin films.

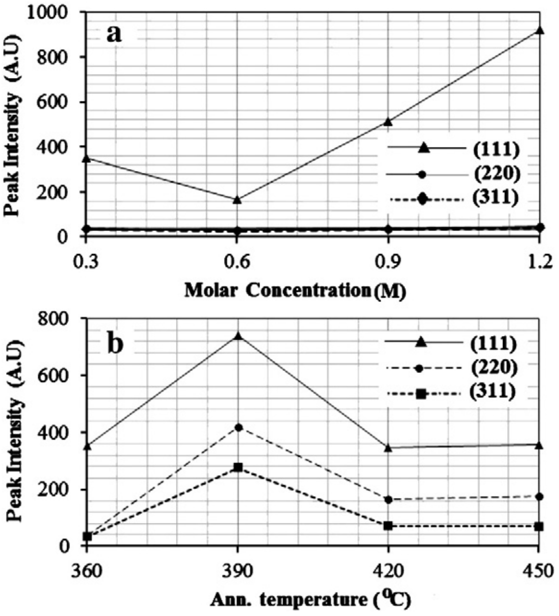

Fig. 2. Variation of XRD peak intensity of the (111), (220) and (311) as a function of the $CdCl_2$ solution concentration for samples annealed at 360 °C (a) and of the annealing temperature for samples treated with 0.3 M $CdCl_2$ (b).

The accurate determination of the lattice parameter '*a*' was carried out using the above equations for all deposited CdTe thin films. The lattice parameters measured for all samples are lower than the powder samples (6.481 Å). The reduction of lattice parameter is due to the decrease on the material strain following the annealing treatment. This is in agreement with Williamson–Hall plots [27] which indicated that the internal strain for the as-grown layers (1×10^{-3} to 5×10^{-3}), was reduced (1×10^{-5} to 7×10^{-4}) after heat treatment. Similar phenomena were also previously observed for metal

Table 1
Calculated values of the structural parameters of $CdCl_2$ treated CdTe thin films.

Sample ID	Angle 2θ, (degree)	Observed d value, (nm)	Plane, (hkl)	Observed intensity, I (A.U)	Lattice constant, a (Å)	Mean cryst. size, D (nm)	Micro strain, ε ($\times 10^{-3}$)	Dislocation density, ($\times 10^{11}$ cm^{-2})
5	23.818	3.732	(111)	353	6.46	93.84	9.2	11.35
(0.3 M/360 °C)	39.371	2.287	(220)	39.4	6.47			
	46.553	1.949	(311)	34.5	6.47			
6	23.914	3.718	(111)	167	6.46	150.54	5.7	4.41
(0.6 M/360 °C)	39.449	2.282	(220)	32.2	6.45			
	46.552	1.949	(311)	24.9	6.46			
7	23.851	3.728	(111)	513	6.46	141.87	6.1	4.97
(0.9 M/360 °C)	39.478	2.281	(220)	36.2	6.45			
	46.584	1.948	(311)	35.0	6.46			
8	23.787	3.738	(111)	913	6.47	170.16	5.1	3.45
(1.2 M/360 °C)	39.342	2.288	(220)	46.6	6.47			
	46.550	1.949	(311)	38.0	6.46			
9	23.787	3.738	(111)	741	6.47	173.57	5.0	3.32
(0.3 M/390 °C)	39.320	2.289	(220)	419	6.47			
	46.461	1.953	(311)	277	6.47			
10	23.809	3.734	(111)	348	6.47	154.99	5.6	4.16
(0.3 M/420 °C)	39.335	2.288	(220)	166	6.47			
	46.484	1.953	(311)	71.7	6.47			
11	23.834	3.730	(111)	356	6.46	197.30	4.4	2.57
(0.3 M/450 °C)	39.358	2.287	(220)	175	6.47			
	46.480	1.952	(311)	70.4	6.47			

organic chemical vapor deposition grown CdTe thin films [28]. However, it is seen that there is a clear increasing trend in *a* following the increase of treated temperature although it did not reach the standard value, suggesting that the compressive stress increases with temperature which acted in the plane parallel to the substrate surface. This stress is caused by the difference in their thermal expansion coefficients, and mostly the lattice mismatch between the CdTe and the underlying glass substrates [29].

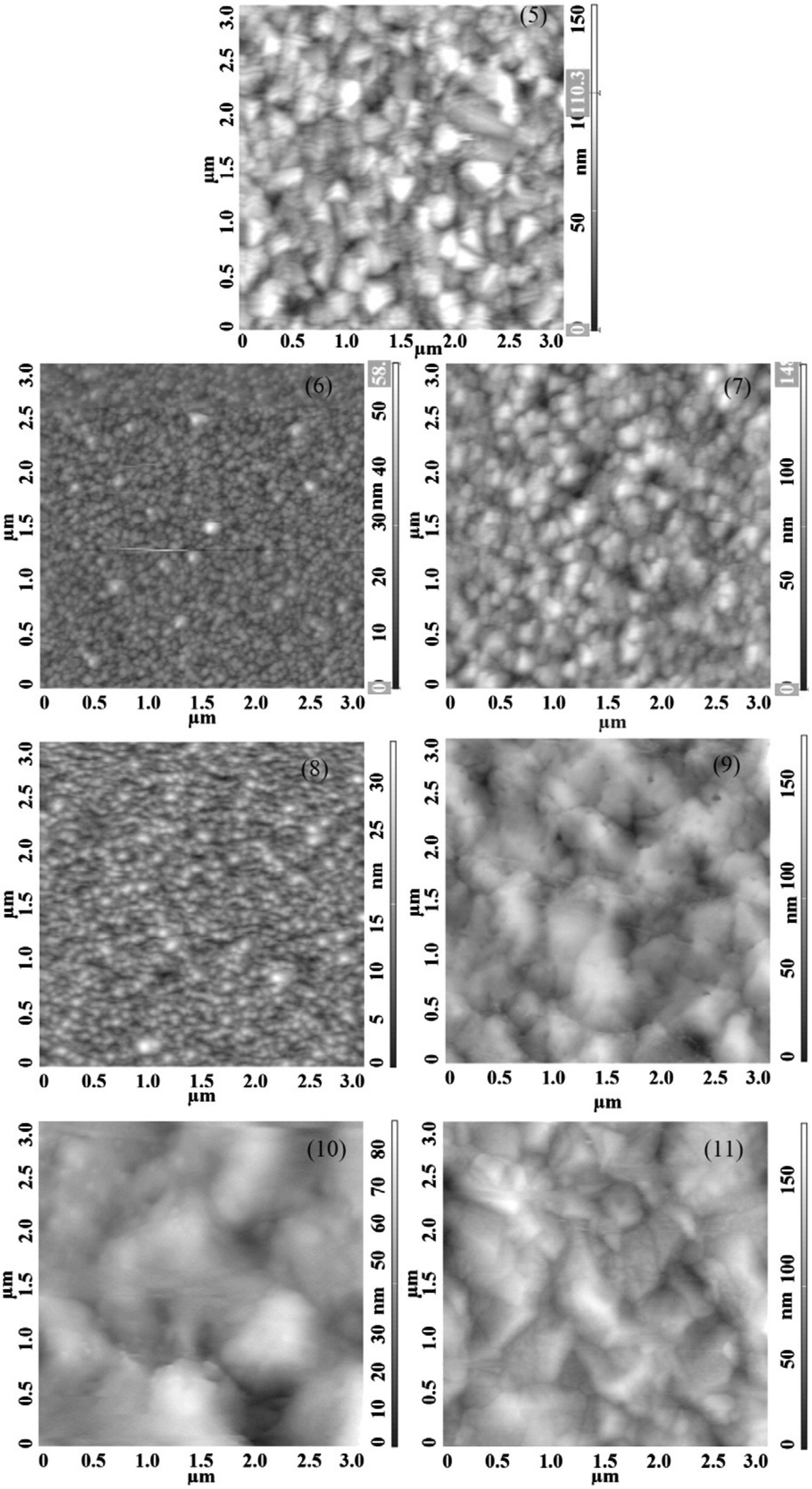

Fig. 3. AFM images of $CdCl_2$ treated CdTe samples (5, 6. 7 and 8) treated at 360 °C with 0.3 M, 0.6 M, 0.9 M and 1.2 M, respectively, (5, 9, 10 and 11) treated at 360 °C, 390 °C, 420 °C and 450 °C, respectively, treated by solution concentration 0.3 M.

It was also found that the mean crystalline sizes of the treated films increased with the increase of solution concentration as well as the increase of treated temperature as shown in Table 1. However, the values of micro-strain and dislocation densities change with little fluctuation and the change of both parameters; e.g. $CdCl_2$ solution concentration and annealing temperature. The highest micro-strain of 9.2×10^{-3} is observed for sample 5, which is treated at 360 °C with 0.3 M solution indicating the highest lattice misfit and dislocation in the film structure [30]. The microstrain as well as lattice misfits are suppressed or reduced by following the increase of solution concentration finally reaching to 5.1×10^{-3} for 1.2 M solution. The reduction is also observed with the increase of annealing temperature with the lowest value of 4.4×10^{-3} at annealing temperature of 450 °C. This indicates that the strains are released at a higher annealing temperature as it is well agreed with the previous discussion. As the microstrains are reduced, the dislocation densities as well as structural defects of the deposited CdTe thin films are reduced and crystalline sizes are increased following the effects.

3.2. Surface topography analysis

The surface topographical effects on CdTe thin films due to post deposition $CdCl_2$ treatment were observed from AFM images as shown in Fig. 3. The change of surface roughness (average and root-mean-square) with the solution concentrations and annealing temperatures are also shown in Fig. 4. The significant effects of $CdCl_2$ treatments are observed for both categories as shown in these figures. The crystals are observed loosely bound triangular shape for the films treated with 0.3 M solution concentration at 360 °C. However, the shape changes to a tiny pyramid shape for the films treated at a higher solution concentration, and a little broader pyramid is found for 0.9 M concentration. The reshaping of the grains as observed may be the cause of $CdCl_2$ sintering effect and the grain widening did not occur due to the absence of enough thermal stress. At higher annealing temperatures (390 °C–450 °C), pyramids are diffused and made into a bigger island as observed from the figures for the samples 9, 10 and 11. From the 2D images; it is observed that the size of the island increases with the increase of annealing temperature until 420 °C and again decreases for 450 °C. This can be attributed to the saturation of diffusion and recrystallization at 420 °C and recrystallization may start again above this temperature. The bigger grains are observed to overlap each other at this stage.

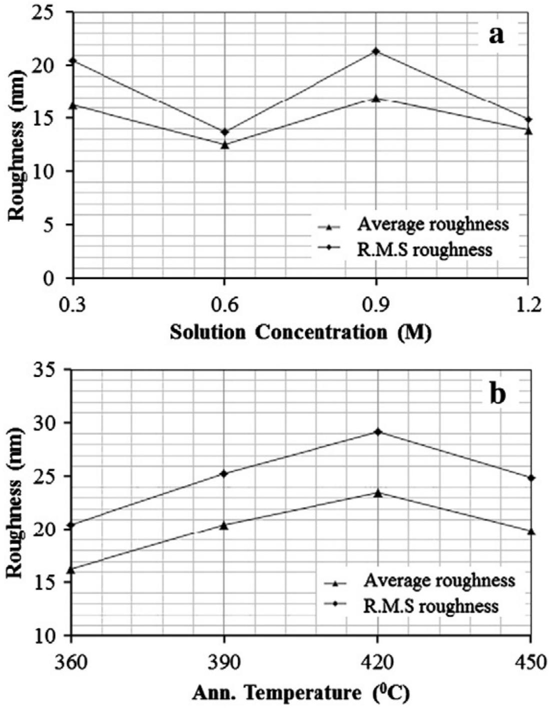

Fig. 4. Variation of average and R.M.S values of roughness of annealed CdTe thin films with respect to the change in (a) solution concentration, (b) annealing temperature.

The treated films are observed to have larger and non-uniform grains as well as random orientation. The results are in concurrence with the XRD patterns. It has been observed that the roughness of the films rise and fall with the concentration, whereas surface roughness of the films linearly increases with the increase of annealing temperature and falling down for the films annealed higher than 420 °C. The decrease of roughness of the film treated over 420 °C gives an indication of the contraction of grains, which is confirmed from the reduction of grain size as seen in SEM image at the next section. The highest roughness is observed to be 20 nm for the sample 7 among the samples treated with different solution concentration and 30 nm for the sample 10 among the samples treated with different annealing temperature.

3.3. Surface morphological analysis

The effects of $CdCl_2$ treatment on surface morphology were also reported by others for the CdTe thin films (relatively thicker) deposited by close spaced sublimation [8], vacuum evaporation [9], molecular beam epitaxy [10], physical vapor deposition [11] and electrodeposition [12]. From all the studies, it was well established that $CdCl_2$ treatments improve the films morphology as well as the grain size. The $CdCl_2$ acts like a sintering flux in CdTe as small grains growth and unite together and make bigger grains, but it also causes the widening of grain boundaries of the grown films. Wider grain boundary regions are not expected for absorber films because they may affect the parallel conduction across the grain boundaries. However, they may also cause the shunting of solar cells by providing a conducting link, helping the diffusion of the top window film and bottom back contact electrodes. For high efficiency and stable solar cells, large grained and compact CdTe is required.

The VPSEM micrographs of the annealed CdTe thin films are shown in Fig. 5. No cracks or pinholes are seen for these samples. As shown in the figure, the films treated at 360 °C with solution of 0.3 M (sample 5) shows prism shaped grains, which are randomly distributed. The film has not been found to be as well compact and smooth. The film treated at higher solution concentration (0.6 M, 0.9 M & 1.2 M) shows a smooth and uniform crack free surface with spherical-shaped grains distributed all over. The grain size reduces as the micro-strains increase with increase of density of nucleation center for the films treated with a higher $CdCl_2$ concentration at 360 °C as seen in the image for samples 6, 7 and 8. These strains are produced parallel to the surface and towards the center of the grains. The grains are found homogeneous in shape even if the shapes are changed according to the solution concentration. The compact surface with well-defined grains, although they are small, is also observed in these cases. The average grain size was found to be 200 nm. The shortage of grain broadening and increase of nucleation center is observed for these films treated at 360 °C, may be due to the absence of enough thermal stress. On the other hand, the treatment conditions were kept constant for the films 5, 9, 10 and 11 as shown in Fig. 5, while the treatment temperature was varied from 360 °C to 450 °C. It is observed that the films treated with a higher annealing temperature improved the grain structure. The grain sizes increase with higher treated temperature due to the decrease of micro-strain [31] as seen in the previous section. The average grain size was found for the films treated at 390 °C and 420 °C to be 500 nm with grains of irregular shapes and sizes. The films show a compact-enough surface as well. A little contraction of grain sizes are observed for the films treated at 450 °C. Some porous spot at the surface is also observed at 450 °C, which may affect the carrier movement and increase recombination. In

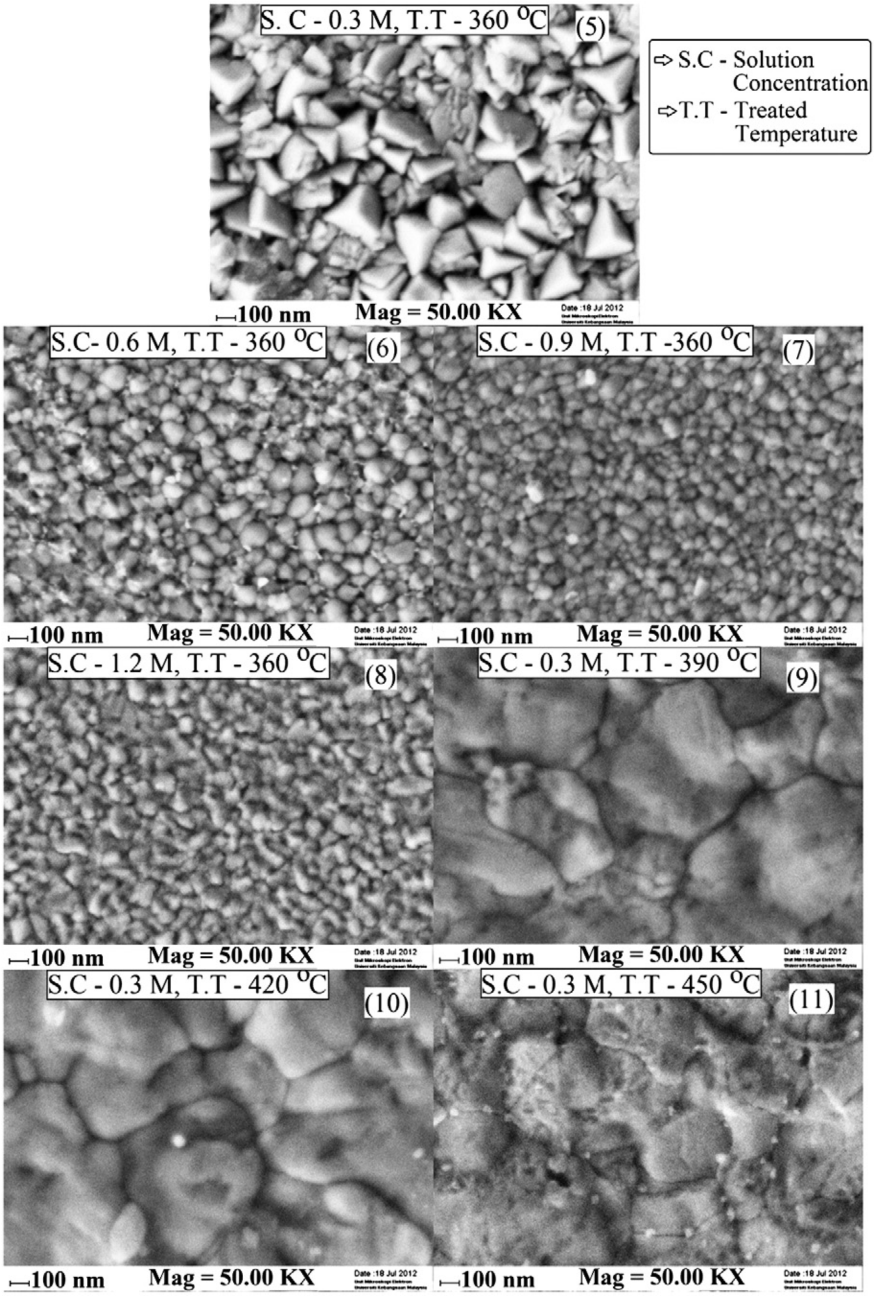

Fig. 5. SEM surface morphology images of $CdCl_2$ treated CdTe samples (5, 6, 7 and 8) treated with 0.3 M, 0.6 M, 0.9 M and 1.2 M $CdCl_2$ and subsequent annealing at 360 °C, and samples (9, 10 and 11) annealed at 390 °C, 420 °C and 450 °C, with $CdCl_2$ concentration of 0.3 M.

summary, it can be concluded that 360 °C annealing temperature is not enough to get the expected grain growth, regardless of whether the dipping solution concentration is high or low. On the other hand, the annealing temperature of over 420 °C appeared to be unsuitable, as the lattice contraction force is developed to the films to reduce the grain sizes. The optimum temperature range can be found within the range of 390 °C to 420 °C for $CdCl_2$ treatment for 1.5–2.0 μm thick CdTe films. The results are in concurrence with the previous investigation [32].

3.4. Electrical characterization

The electrical properties of the CdTe layers were investigated at room temperature by resistivity and Hall Effect measurements with an integrated resistivity/Hall measurement system (ECOPIA 3000). In this case, the magnetic field was applied perpendicularly to the surface of the sample and the magnitude and polarity of this were alternated periodically, while a direct current was passed across the sample using one diagonal pair of the four gold electrodes connected to a current source. Then, by a frequency response analyzer (HMS-3000), alternating Hall voltage induced synchronously with the ac magnetic field was detected using the other pair of electrodes. The detection limit of the Hall voltage has significantly improved by following this method. The magnitude of the magnetic field and the current source was 0.55 T at the maximum and 50 nA, respectively. The carrier concentration, mobility, resistivity and Hall coefficients were deduced from this study.

The bulk and surface carrier concentration found from the Hall Effect measurements for the samples are plotted in Fig. 6. Each bulk carrier density is in the order of 10^{13}–10^{14} cm^{-3} and surface carrier density is in the order of 10^{9}–10^{10} cm^{-2}. As seen in Fig. 6, there is a

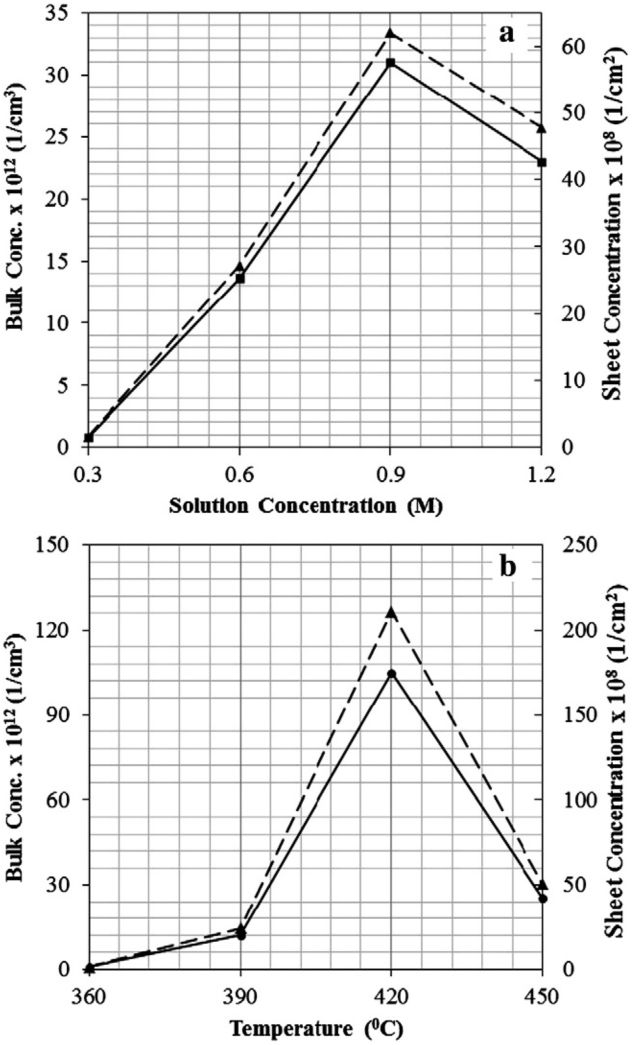

Fig. 6. Variation of bulk and sheet carrier concentration in annealed CdTe thin films with respect to the variation in (a) $CdCl_2$ solution concentration, (b) annealing temperature.

tendency for the carrier density either bulk or surface of the CdTe thin films to increase with the increase of $CdCl_2$ solution concentration until 0.9 M, thereafter decreasing for further increase of concentration. Moreover, an almost similar tendency is observed with the increase of treated temperature from 390 °C to 420 °C with a sharp decrease at 450 °C. The highest carrier concentration is observed to be $3.1 \times 10^{13}/cm^3$ for sample 7, treated with 0.9 M $CdCl_2$ concentration with subsequent annealing at 360 °C among the samples treated with different solution concentration. Moreover, another higher carrier concentration of $1.05 \times 10^{14}/cm^3$ was also found for sample 10, which is treated with 0.3 M solution and annealed at the temperature of 420 °C among the samples annealed at different temperatures.

The measured mobility, resistivity and Hall coefficients are presented in Table 2. The values of resistivity show similar orders to those reported by other groups (10^4–10^8 Ω-cm) [33–35]. The highest mobility is observed for sample 8, where it exhibits the lowest resistivity and the lowest Hall coefficients among the samples treated with different solution concentrations. On the other hand, the highest mobility is observed for sample 10, although it shows the highest resistivity among the samples treated with different temperatures. It may have happened because the carrier density of this sample is almost 10 times higher than the other films. The Hall coefficient is also the lowest for sample 10, which is treated by 0.3 M $CdCl_2$ solution with subsequent annealing at 420 °C among all others indicating the highest carrier generation.

Table 2
Electrical properties of $CdCl_2$ treated CdTe thin films.

Sample ID	Mobility (cm^2/V-s)	Resistivity [x10^4] (Ω-cm)	Hall Coefficients [x10^5] (cm^3/C)
5 (0.3 M/360 °C)	21.10	37.3	127.7
6 (0.6 M/360 °C)	27.35	1.67	10.7
7 (0.9 M/360 °C)	30.12	6.59	7.89
8 (1.2 M/360 °C)	53.10	0.49	6.78
9 (0.3 M/390 °C)	14.30	7.64	18.6
10 (0.3 M/420 °C)	67.40	8.77	2.44
11 (0.3 M/450 °C)	15.40	1.57	12.6

4. Conclusion

The structural and electrical properties of the $CdCl_2$ solution treated sputter-grown CdTe thin films have been studied through XRD, AFM, SEM and Hall Effect measurements. Recrystallization and development of polycrystalline CdTe structure were observed in XRD analysis for CdTe films annealed at 390 °C and above. The films annealed at different temperatures (390 °C to 450 °C) have been found with total random orientation, which increased with the increase of annealing temperature. From AFM analysis, it has been revealed that the annealing temperature affects more drastically than the solution concentration to the surface roughness of the CdTe thin films. The highest roughness is found to be 20 nm for the samples treated with 0.9 M solution among different solution concentrations and 30 nm for the sample annealed at 420 °C among different annealing temperatures. Although, the sintering effect of $CdCl_2$ solution was observed but no grain broadening was observed from SEM images for films treated at 360 °C with 0.3 M to 1.2 M concentrations. The bulk carrier concentration has been found in the range of 10^{13} to 10^{14} cm^{-3} with the highest carrier concentration at $1.05 \times 10^{14}/cm^3$ for the CdTe film treated at temperature of 420 °C with 0.3 M solution. Therefore, it can be concluded that, a 0.3 M $CdCl_2$ aqueous solution for $CdCl_2$ treatment with optimum annealing temperature range of 390 °C to 420 °C for subsequent annealing for 15 to 20 min. is suitable for 1.5–2.0 μm thick high quality CdTe thin film absorber layers.

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